REPORT DOCUMENTATION PAGE

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE Feb. 96	3. REPORT TYPE AND DATES COVERED Technical Report.

4. TITLE AND SUBTITLE

Interannual Variability of the Atlantic Water in the Arctic Basin

5. FUNDING NUMBERS

N/A

6. AUTHOR(S)
S.V. Pisarev

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Marine Science International Corporation

8. PERFORMING ORGANIZATION REPORT NUMBER
MSIC Report No. 2/96

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

SERDP
901 North Stuart St. Suite 303
Arlington, VA 22203

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

N/A

11. SUPPLEMENTARY NOTES
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12a. DISTRIBUTION / AVAILABILITY STATEMENT	12b. DISTRIBUTION CODE A
Approved for public release: distribution is unlimited	

13. ABSTRACT *(Maximum 200 Words)*

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The second part of this report considers the results of processing and analysis of the signals transmitted during the Transarctic Acoustic Propagation experiment from the ice camp TURPAN and received at the ice camp NARWHAL. The main goal of this study is to determine the propagation loss of individual acoustic modes in the signals transmitted across the Arctic Basin to the Lincoln Sea.

14. SUBJECT TERMS Acoustic Propagation, Arctic Ocean, SERDP			15. NUMBER OF PAGES 28
			16. PRICE CODE N/A

17. SECURITY CLASSIFICATION OF REPORT unclass.	18. SECURITY CLASSIFICATION OF THIS PAGE unclass.	19. SECURITY CLASSIFICATION OF ABSTRACT unclass.	20. LIMITATION OF ABSTRACT UL

19980709 132

MARINE SCIENCE INTERNATIONAL CORPORATION

INTERANNUAL VARIABILITY OF THE ATLANTIC WATER IN THE ARCTIC BASIN

S.V. Pisarev

ANALYSIS OF THE RESULTS OF THE TRANS-ARCTIC PROPAGATION EXPERIMENT
(Transmissions from i/c TURPAN to i/c NARWHAL)

A. N. Gavrilov
M. Yu. Andreyev

MSIC Report No. 2/96

1996

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S.V. Pisarev

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I. INTRODUCTION

According to hydroacoustic models of the Arctic Basin, variability of the Atlantic Water is best determined using the methods of transoceanic acoustic propagation [17]. According to modern oceanographic thinking, the characteristics of this water indicate interannual variability [20]. However, apart from Timofeev and Bulatov et al. [10, 29], no one has yet conducted estimates of this variability over long periods of time, and in the vast region of the Arctic Basin. Recently, the amount of data has increased and there is new thinking on the oceanography of the Arctic Basin. So, we anticipate success in new investigations of the interannual variability.

In the last five years, some of the oceanographic measurements in several regions of the Arctic Basin, demonstrate noticeable warming of the Atlantic Water relative to climatology data [11, 12, 23, 24]. The TAPEX-94, when compared with the modeling results which were obtained from the oceanographic data of 1973-79, also demonstrates warming [17]. However, it is still impossible to say, whether this warming is a result of interannual variability, incidental phenomenon, or long-term transition from one stable water mass structure to another [2, 9].

For all of the above-mentioned reasons, we give, in this report, the results of the research on Atlantic Water interannual variability, on the basis of all available CTD observations. It is assumed, that the reader is acquainted with the main thinking on the general oceanography and interannual variability of the Arctic Basin. Otherwise, we recommend, the brief review written by Pisarev [20].

II. THE CONCEPT OF THE DETERMINATION OF VARIABILITY

There are two basic approaches to the study of interannual ocean variability and variability of longer periods. The first method is to compare two or more oceanographic sections, carried out at close tracks. The second approach is to compare a statistically sufficient number of data, averaged within a certain region and within a certain period of time. An example of the first approach is given in [16], and the example of the second one is in [6]. However, there are no sections duplicated in the Arctic Basin and large spatial-temporal irregularity [26, 33] is also inherent in the Arctic Basin oceanographic data. These obstacles almost rule out the application of a formal statistical approach. Therefore, there is only one way to compare individual stations.

Any attempt to compare individual stations requires definition of the maximal spatial span between different stations which could be omitted. The determination of that span requires an understanding of spatial variability. What is known about spatial variability of the Arctic Basin has undergone a significant evolution, though it is still at the stage of expert estimations. In the beginning, from the analyses of the limited number of stations, a frontal zone was found above the Lomonosov Ridge [22, 28, 29]. With the increase in the number of measurements, it was concluded, that significant horizontal gradients exist in narrow boundary currents, situated at the margins of the Arctic Basin and in the regions of the main high points of the bottom relief [1]. Since 1987, classical oceanographic sections in the Arctic Basin have been made with the use of icebreakers [5]. As a result, it turns out that the spatial variability in the Arctic Basin is greater than that assumed earlier [4].

With the increase in the number of data, attempts at separation into regions, with similar water properties, were undertaken. Thus, data over thirty years, up to 1974, formed the basis for the determination of regions with typical T/S and chemical structures [14] (pp. 136, 164), (Fig. 1, 2). The margins of such structural zones are very close to each other. It follows, that the distribution of chemical and T/S characteristics are basically due to climatic conditions, and to large-scale circulation.

The theories on the Arctic Basin circulation were proposed after thorough analysis of measurements of the currents, and physical and chemical oceanographic observations. A recent scheme of the circulation of the Atlantic Water in the Arctic Basin was proposed in 1994 [25], (Fig. 3). This scheme

Fig1. Typical T/S structures of water masses in the Arctic Basin
(according to Gorshkov, 1980, p. 136).

Fig2. Typical chemical structures of waters in the Arctic Basin
(according to Gorshkov, 1980, p. 164).
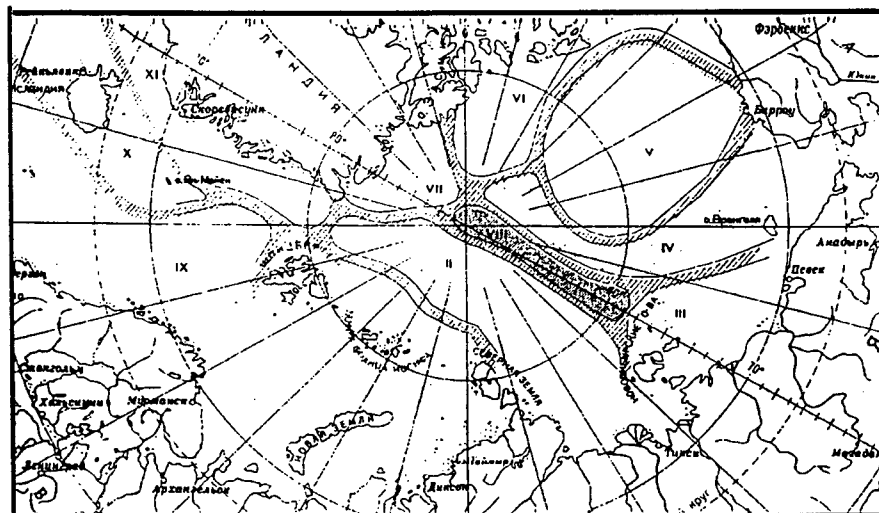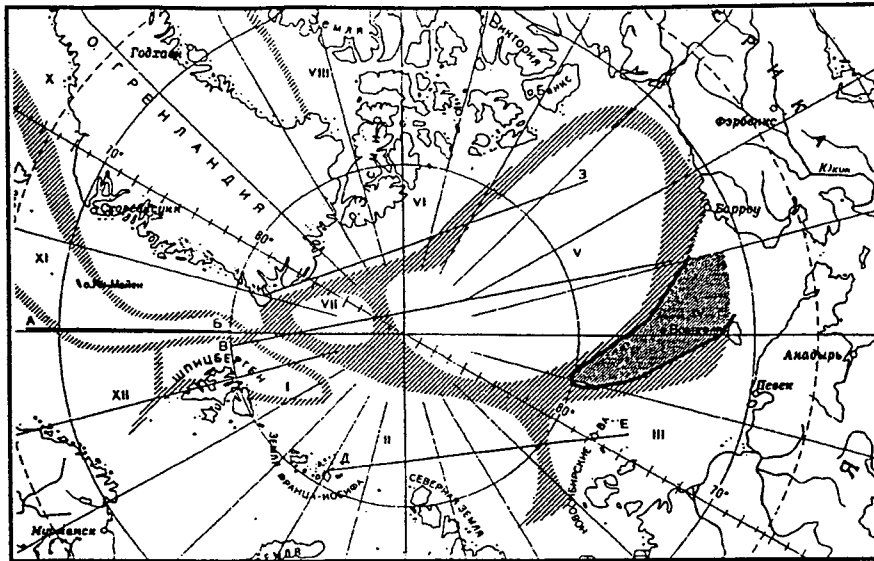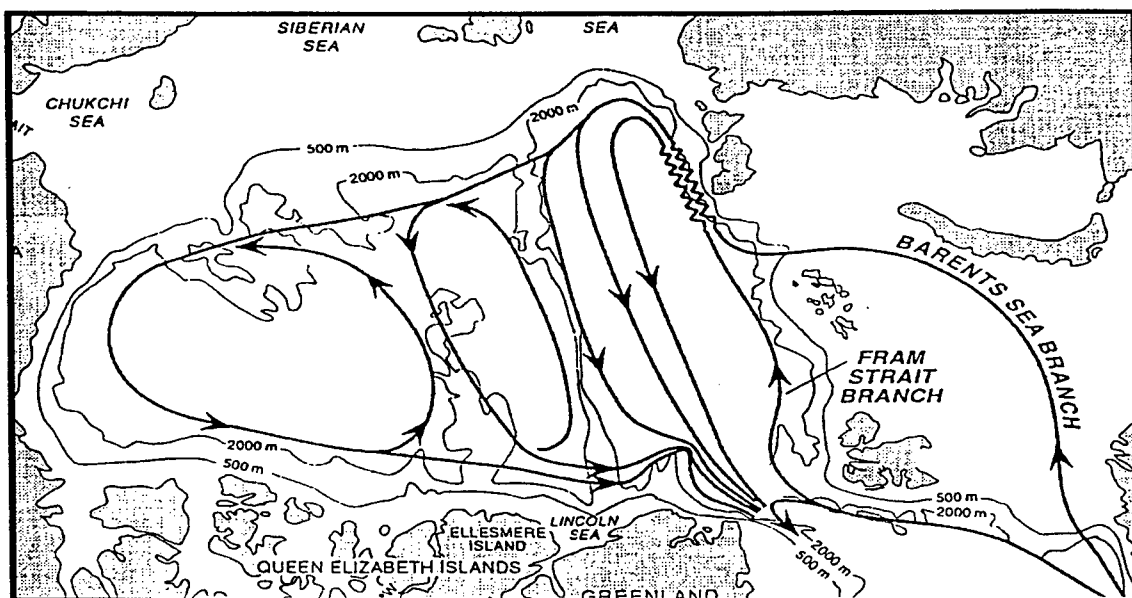
Fig3. Schematic diagram showing the inferred circulation, in the Arctic
Basin, of the Atlantic Layer and intermediate depth waters, between
200 and 1700 m (according to Rudels et al., 1994).

is a result of the development of the earlier diagrams of circulation [1, 13, 14, 29, 30, 31]. Some authors have pointed out that the schemes of regions and schemes of circulation coincide, in general, with large-scale features of the bottom relief [4]. Modern models also demonstrate that large-scale circulation is controlled by the bottom relief [27]. These models also demonstrate strong boundary currents.

All of this corresponds to the theories presented in [1, 2]. The main idea behind these theories is that the Arctic Basin may be separated into two kinds of regions - the regions of the boundary currents along the main high points of the bottom relief, and the regions above the abyssal plains (the regions of the basins). The boundary currents occupy zones of several tens of kilometers in width. In these zones the greatest speeds have been observed. Perhaps, the main transport of the Atlantic Water occurs in such zones. The variability in the "basin" regions is small. There the speeds of the currents are not too high, and local processes control the advection.

Let us consider the interannual variability of the Atlantic Water in the regions shown in Fig. 4. The regions of the boundary currents and the regions of the Amundsen, Makarov and Canadian Basins are separated in Fig. 4.

Firstly, after visual analysis of long range quasisynoptic sections, we determined the meridional extent of the boundary current zone. The sections performed by the icebreakers *Polarstern* in 1987 and *Oden* in 1991, characterize the distribution of the temperature and the salinity in the Western part of the Eurasian Basin [4, 5, 15]. These sections show that the sizes of the horizontal gradients of temperature and salinity in the Atlantic Water layer decrease, notably, northward of the Gakkel Ridge. This is also confirmed by the horizontal distribution of the potential temperature maximum [11]. Furthermore the boundary between the different chemical properties, in the Eurasian Basin, is over the Gakkel Ridge (Fig. 2). It is assumed that the zone of active heat loss of Atlantic Water extends from the continental slope of Svalbard and Frans-Josef Land up to the Gakkel Ridge [7]. All of the above-mentioned facts forced us to bound regions 1-4 by the continental slope on the one side, and by the Gakkel Ridge on the other side.

One more section was carried out by the ships *Polar Sea* and *Louis St. Laurent*, in 1994. These ships crossed the Chukchi Plateau, the Mendeleev-Alfa Ridge, the Lomonosov Ridge and the Makarov Basin along the 180° meridian [12]. According to the preliminary results from this expedition and the results of ship *Henry Larsen* -1993 [11], the largest horizontal gradients are located in the zones of changes of the bottom depth - ridges and continental slopes. Following this, we assumed, that the margins of the "boundary current" regions 5, 7-12, 14, 16, 20, 21 correspond to the geomorphological elements of the bottom relief such as slopes, ridges and mountain areas [14]. Regions 6, 13, 15, 17-19 correspond to abyssal plains.

As mentioned above, the oceanographic data of the Arctic Basin are characterized by great spatial and temporal irregularity and deficiency. Therefore, when investigating interannual variability in a small region, it is possible to analyze the data only on short timescales, on the order of a few years. With an increase in area of a region under research, another problem can arise. The data of a particular year may show opposite tendencies. In fact, water property anomalies may show in one part of the region, and not in others. This can be found for anomalies inflowing through the Fram Strait or through the St. Anna Trough. On the other hand, it is most likely that there is Atlantic Water anomaly formation as a result of interaction with shelf waters. It is also possible that the Atlantic Water anomaly can be generated inside the Arctic Basin due to local processes.

Such understandings of the formation and spreading of anomalies have led us to divide the boundary current zones, along the continental slope, into sections of 30 - 40 degrees of longitude. Accepting, roughly, the residence time of Atlantic Water in the large cyclonic loops of about 20 years [25], we conclude that the Atlantic Water passes through those sections in two years. In some cases we specified

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Fig.4 Schematic diagram showing the inferred regions in the Arctic Basin, with similar spatial gradients and similar interannual variability of Atlantic Water.

the longitudinal sizes of the regions based on other reasons. For example, region 1 coincides with structure II of the water masses (Fig. 1) [14, 19]. Regions 2 and 3 were separated to take into account the possible inflow of the Atlantic Water through the Barents Sea. (It is still impossible to speak with certainty about the direction of the Atlantic Water movement through the St. Anna Trough. Russian authors have demonstrated that the Atlantic Water flow is directed from the Arctic Basin to the Kara Sea [14, 19, 29], while most western scientists have come to the opposite conclusion).

Region 4 was marked out as an area of strong transformation of the Atlantic Water in the region of the "Great Siberian Polynya", which, possibly, includes the interaction of two flows of the Atlantic Water[19, 25]. Region 20 - the Morris Jesup Plateau, coincides with T/S structure VII (Fig. 1)[14, 19]. The separation of the regions of the Lomonosov Ridge, Amundsen Basin, Makarov Basin, Canadian Basin, and the Mendeleev-Alpha Ridge, into two parts, is the result of a compromise between the intention to make more measurements for each region, and the knowledge that opposite changes may take place during one year, within a large region.

We assumed, that the regions marked on Fig. 4, have similar spatial gradients in the Atlantic Water layer. The values of the horizontal gradients typical of each region, defined the maximal distance between the stations taken for comparison. The consistency of gradients also provided a comparison of accuracy. Thus, after the analysis of various sections [3, 4, 5, 8, 18, 20] a 10 km distance was chosen for region 1.

We have no continuous sections for all the regions. Therefore, we have estimated the horizontal gradients by individual stations and have chosen the maximal distance for the regions of boundary currents (except in region 1) as much as 20 km, and for the "basin" regions - 50 km.

Looking ahead, it is necessary to note, that the comparison of individual stations has not yielded good results. We have found only 200 places in the entire Arctic Basin which were acceptable for comparison of he stations obtained in different years. Each place was characterized by data of 2 or, sometimes, 3-5 years. These years represented a narrow range of the time of oceanographic observations in the Arctic basin. Half of these 200 places are located in region 1. However, it is difficult to separate the spatial variability from temporal changes in this region. Therefore, we decided to apply another method of investigating interannual variability. We decided to compare all existing stations with the climatology data. This method allowed us to distinguish the temporal variability in spatial-temporal changes. The results of comparison by the first method did not contradict the results of comparison by the second one. Therefore, further discussion will be conducted, mainly, on the basis of comparisons with climatic fields.

As a rule, only one expedition a year was conducted in the Arctic Basin. Sometimes 2-3 expeditions worked during one and the same year in remote regions. Thus, we had no reason to look for the existence of small systematic errors in the data of a single expedition. Therefore, we assumed that all stations were correct after our control (see section **The Method of Calculations**).

Let us list the main assumptions expected in this report for the analysis of interannual variability:

1. the scheme of Atlantic Water circulation in the Arctic Basin is correct (Fig. 3);

2. the interannual variability within the regions shown in Fig. 4 is assumed to be homogeneous;

3. the climatic fields of temperature and salinity used adequately describe the spatial variability of the Arctic Basin;

4. all stations passed through the test are correct.

III. DATA

The data, used in our investigation, are presented in Table 1. We restrict the Arctic Basin to the following boundaries: 15°W-105°E 80°N; 105°E-110°E 79°N; 110°W-130°W 77.5°N; 130°W-140°W 78°N; 140°W-160°W 79.5°N; 160°W-170°W 77°N; 170°W-170°E 75°N; 150°E-170°E 71°N; 135°E-150°E 70°N; 130°E-135°E 71°N; 125°E-130°E 75°N; 115°E-125°E 78°N; 90°E-115°E 80.5°N; 15°E-90°E 82.5°N.

A description of the POLEX data and algorithms for gridding these data are presented in [26]. Briefly, the original data were interpolated on to five selected tracks 100 km apart. The distances between the original stations were 200-300 km. The Winter and Summer climatic T/S profiles in the Arctic Ocean (Arctic Basin and Siberian Seas) were constructed from 1367 winter and 4000 summer stations [21]. These data have been obtained from Russian drifting stations, ships and aircraft surveys during the years 1955-1980. The T/S values at all of the standard oceanographic levels were interpolated on to the points of a regular grid with a step of 55.6 km.

IV. THE METHOD OF CALCULATIONS

In our research, it was accepted that the 0° isotherms were the upper and lower margins of the Atlantic Water layer. The average weighted temperature, (from now on it will be referred to as the average temperature) the maximum temperature, the thickness, and the heat content were calculated for this layer. These characteristics were calculated for the observed (experimental) stations, and for the climatic profiles.

The characteristics of climatic profiles were interpolated from their initial gridded points to the coordinates of each observed station. Then, the characteristics of the observed stations were compared with the climatic ones. For each region (Fig. 4) the stations were chosen such that the depths were deeper than the climatic depth of the lower Atlantic Water margin minus 100 m. The stations should have one or more observation per 100 m. Calculations for each observed station were carried out as follows:

1. If the value of temperature or salinity at one of the depths was not missing, it was interpolated using the values of the adjacent depths. If two neighboring values of temperature or salinity were missing, and the distance between these and next depth exceeded 25 m, such stations were excluded from our investigation. If two neighboring values of temperature or salinity were absent, and the distance was less than 25 m, the values were interpolated to these depths using the values of adjacent depths. The number of stations, which remained in each region after satisfying Item 1 was named "the number of stations in the Oceanographic Data Base" in the section entitled **Results of Calculations in the Regions**.

2. The depths of each station were arranged in order of increasing depth. The detailed data of the CTD profiles were divided into 10 m intervals to have only one crossing with the 0° isotherm on the top or on the bottom margin of the Atlantic Water.

3. The top margin of the Atlantic Water was determined as the depth at 0°, where the temperature changed sign from negative to positive. The maximum temperature of the Atlantic Water was defined as the maximum positive value. The bottom margin of the Atlantic Water was defined as the depth at 0°, where the temperature changed sign from positive to negative. If the temperature values did not change sign from a positive value to a negative one, the bottom margin was determined by extrapolation, using the values of temperature in the deepest depth and the depth of the maximum temperature. The salinity was similarly calculated for the lower margin.

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Table 1.

Data Set Description	Location deg. min. or region	Time month. years	Quantity of stations (sts).
World Ocean Atlas (WOA) - 94	Arctic Basin	06.1905-10.1990	4982 sts
"Narwal" Ice Camp (USA-Canada)	Lincoln Sea 83.33 - 83.35 N 62.59 - 63.14 W	04.1994	19 sts
Oden-91, Swedish RV (only little part of observations)	83.33 - 83.35 N 27.38 - 27.58 E	08.1991	2 sts
"Turpan" Ice Camp (Russia-USA)	83.17 - 83.35 N 23.45 - 27.23 E	04.1994	6 sts
Fram, Norwegian RV (famous Nansen expedition; part of observations)	80.25 - 85.30 N 59.06 - 132.04 E	04.1894 - 11.1995	4 sts
Nautilus, American submarine	81.40 - 81.21 N 11.00 - 21.00 E	06.1931	5 sts
"North Pole -1", Russian drifting station	80.23 - 88.53 N 06.15W - 23.48E	06.1937 - 12.1937	28 sts
Sedov, Russian RV (part of observations)	85.29 - 86.23 N 40.36 - 123.54 E	11.1938 - 09.1939	9 sts
H - 169, Russian aircraft (part of observations)	78.28 - 81.37 N 176.44 - 179.12 E	04.1941	2 sts
Some results of Russian aircraft expeditions	80.04 - 86.56 N 157.20W - 142.09 E	04.-0.5 of 1948, 1949, 1950, 1955	16 sts
Some Russian expedition on a drifting ice (little part of observations)	80.51 N 109.43 E	04.1951	1 sts
Litke, Russian RV (little part of observations)	81.40 N, 9.23 E	09.1955	1 sts
"North Pole -5", Russian drifting station (part of observations)	85.24-86.46 N 82.23-120.44 E	11.1955 - 11.1956	5 sts
"North Pole-6", Russian drifting station (part of observations)	82.25 - 86.31 N 53.40-142.15 E	06.1958 - 03.1959	4 sts
"North Pole-7", Russian drifting station (part of observations)	85.41 - 86.22 N 44.26 - 157.25 W	01.1958 - 03.1959	3 sts
"North Pole-13", Russian drifting station (main part of observations)	78.14-85.55 N 91.30-170.23 E	05.1965 - 04.1966	22 sts
"POLEX" - gridded data from Russian quasi-synoptic aircraft surveys of the Arctic Basin	lines between cape Barrow and 1. Svalbard; 2.Frans-Josef Land; 3. Severnaya Zemlya and Lincoln Sea and 4. Svalbard; 5. .Frans-Josef Land	03-05 of 1955-56, 1973-79	711 sts
"Scicex95", American submarine SSXCTD data	section between 72N, 150W and 85N, 51E.	04.1995	63 sts
Winter and Summer profiles of Climatic Fields of the Arctic Ocean-94	Arctic Basin		3339 sts

Linear interpolation and extrapolation were used in all cases. Stations, for which any one parameter was not defined, were excluded from our investigation.

It is necessary to note, that because of formal data quality control, unrealistic stations with good quality flags are found in WOA94 [33]. For example, at some of such stations, positive temperatures in the range 2°-4° in the whole layer between 0 m and 1000 m are observed in the central part of the Arctic Basin. Such stations were completely excluded in our calculation procedure. The stations from the other sources had no gross errors.

4. The heat content was calculated as, $Q = \int_{h_2}^{h_1} c_p pT\,dz$,

where c_p - specific heat content of the sea water [32];

   p - density of the sea water [32];

   $h1$ and $h2$ - the top and the bottom margins of the Atlantic Water.

   Tw - the temperature of the Atlantic Water.

Determinations of the Atlantic Water temperatures, heat content and thickness for the climatic profiles were carried out similarly to these calculations for the observed stations. To compare the characteristics of an observed station with the climatic characteristics, the latter were calculated by interpolation between three gridded points.

In our view, the formal criteria we used for the selection of stations were reasonably modest and allowed us to use the maximum possible number of stations for the investigation of interannual variability. The modesty of formal criteria was compensated by subjective control of all extreme results.

V. RESULTS OF CALCULATIONS IN THE REGIONS.

Region 1 - the region of Svalbard Island. Coordinates: 0°-35° E, 80°-86°N. There are 1748 stations in the oceanographic data base (ODB), 523 of them chosen for the determination of interannual variability.

Region 1 is the region of the Atlantic Water inflow to the Arctic Basin. This region coincides with structure I of water masses [14, 19]. Large spatial variability due to complex circulation of the West Spitsbergen Current is observed in this region [3, 5, 8, 18]. When the frontal zone of Fram Strait shifts to the east, additional spatial variability can be observed here.

Anomalies of the Atlantic Water thickness and the Atlantic Water average temperature (Fig. 5) highlight the difficulty of separating the spatial variability and temporal changes in this region. Therefore, the pattern with time was calculated in this part of the region, where, most likely, the frontal zone of the Fram Strait does not penetrate. This part is situated to the west of 10°E. It was also decided to conduct our investigations in a region which is situated far from the zone of intensive processes on the continental slope, and from the zone of Atlantic Water recirculation. This part of region 1 is located to the north of 81°N. The ranges of the anomalies in the selected part of region 1 are smaller than those of the whole region (Fig. 5, 6).

The large heat contents of the Atlantic Water in 1931-35 and 1985 are most notable in Fig. 5, 6. The increase of the heat content is caused by the increase in the Atlantic Water thickness, but not by the growth of the average temperature. We have 7 stations from the American submarine *Nautilus* in 1931, 20 stations in 1985, and 6 stations from the ice camp "Turpan" in 1994.
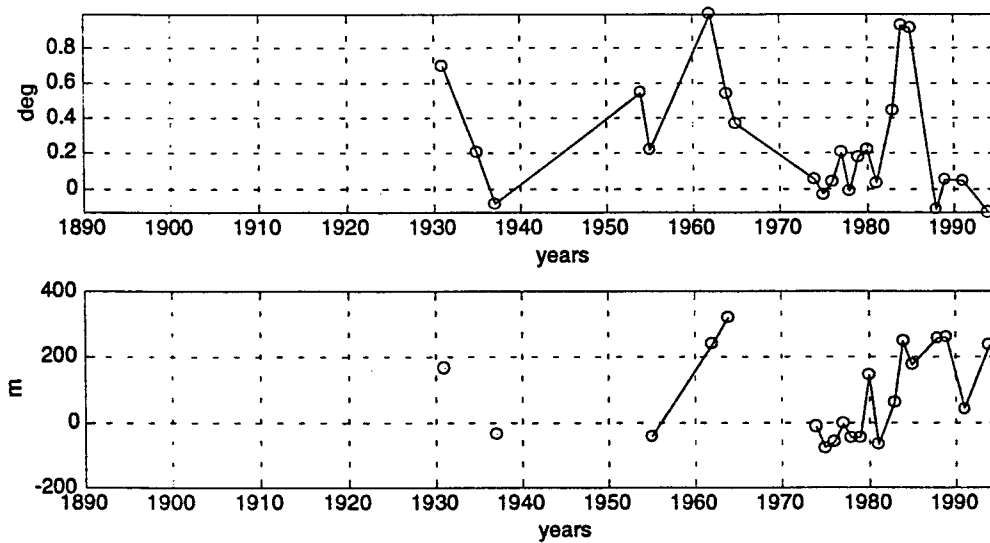
Fig. 5. The interannual anomalies of the average temperature (above) and thickness (below) of the Atlantic Water in region 1 - the region of Svalbard Island.
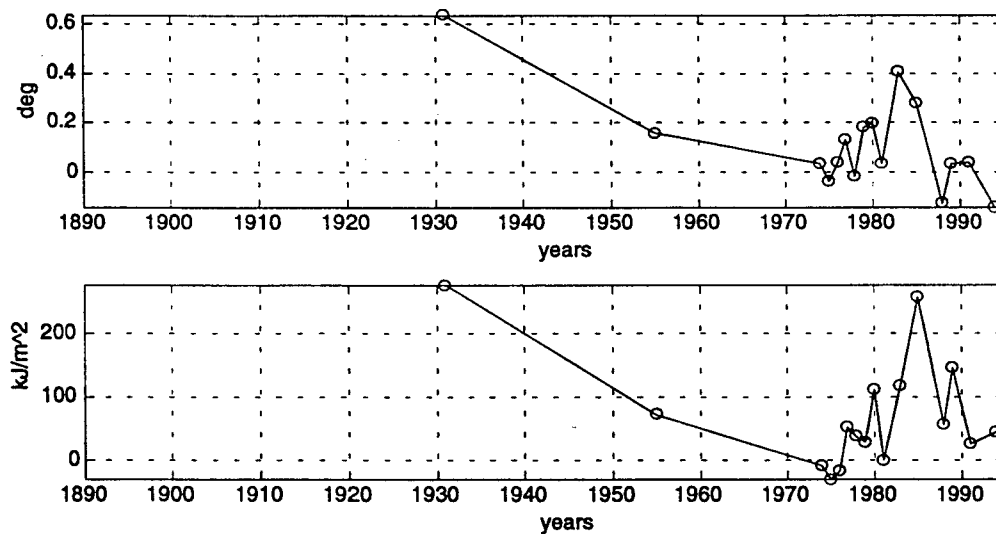

Fig. 6. The interannual anomalies of the average temperature (above) and heat content (x10^4) (below) of the Atlantic Water in the north-eastern part of region 1 (northward from 81°N and eastward from 10°E).

Region 2 - the region of Frans-Josef Land. This region is situated between the southern margin of the Arctic Basin and the Amundsen Basin (regions 6 and 19), within the longitude limits of 35°E- 65°E. There are 157 stations in the ODB, 66 of them chosen for determination of interannual variability.

Significant warming is most marked from the time of the drift of the "Fram" (1895) to the time of the drift of the "Sedov" (1939) (Fig. 7). The results of observations of the American submarine in 1995 show modern warming. The value of this new warming is similar to that mentioned above. In Fig. 7 we can see that the increase in the heat content is not always connected with increases in the maximum temperature. This is true not only for the bottle measurements (1895-1939), but for CTD soundings as well (1988). In addition, the observations of the icebreaker *Rossiya* in this region [23, 24] showed a maximum temperature anomaly up to +1° in 1990.

Region 3 - the region to the northwest of Severnaya Zemlya. Coordinates 65°E-90°E, 80°-86°N. There are 27 stations in the ODB, 18 of them chosen for the determination of interannual variability.

All of these relevant characteristics of the Atlantic Water increase from the time of the famous "Fram" expedition to the time of the expedition of Russian ship *Sedov*. Then, according to aircraft expedition and drifting station results, these characteristics decrease up to the years 1955-56 (Fig. 8). According to the POLEX results, these decreases continue up to the years 1973-79. In accordance with the measurements from the icebreaker *Rossiya*, the maximum temperature anomaly reached +1° in this region, in 1990 [23, 24].

Region 4 - the region to the northeast of Severnaya Zemlya. It is situated between the southern latitude margins of the Arctic Basin and the Amundsen Basin between 90°E-130°E. There are 73 stations in the ODB, 67 of them chosen for the determination of interannual variability.

This region is characterized by the strong transformation of one or two branches of the Atlantic Water, in the area of the "Great Siberian Polynya" [19, 25]. Our data allow us to notice only an increase of the average temperature, the maximum temperature and the heat content from the time of the "Fram" expedition to the time of aircraft expeditions in 1949 and 1955. The decrease in all of the above mentioned characteristics was observed from 1949, 1955 to 1966, and in the 1970's (Fig. 8).

Region 5 - the eastern part of the Lomonosov Ridge. This region includes the part of the continental slope within the limits of 125°E-150°E and the part of the Lomonosov Ridge from the continental slope up to the North Pole. There are 34 stations in the ODB, 34 of them chosen for the determination of interannual variability. It is assumed that part of the Atlantic Water returns toward Fram Strait in this region. On the other hand, the Atlantic Water also flows from the Canadian Arctic Archipelago (Fig. 3). It is impossible to separate these two flows on the basis of our data. The temporal record of all of the characteristics is more or less identical in this region. This record is characterized by growth from 1950 to 1965, and by further decrease from 1973-1979. After 1979 the thickness of the Atlantic Water decreases, the heat content is almost constant, and the average and the maximum temperature grow up to 1985 (Fig. 9).

Region 6 - the eastern part of the Amundsen Basin. The southern margin of the whole Amundsen Basin is - 0°-40°W, 86° N; 0°-90° E, 87° N; 90° E-105° E, 86° N; 105° E-120° E, 85° N; 120° E-125° E, 84° N; 125°E-130° E, 82°N; 130°E-137°E, 80°N. The northern margin - 89°N. Region 6 is located to the east of 50°E. The spatial distribution of the stations compelled us to divide the Amundsen Basin into these parts, since there are no stations between 10°E and 50°E. There are 73 stations in the ODB, 70 of them chosen for the determination of interannual variability in the eastern part of the Amundsen Basin.
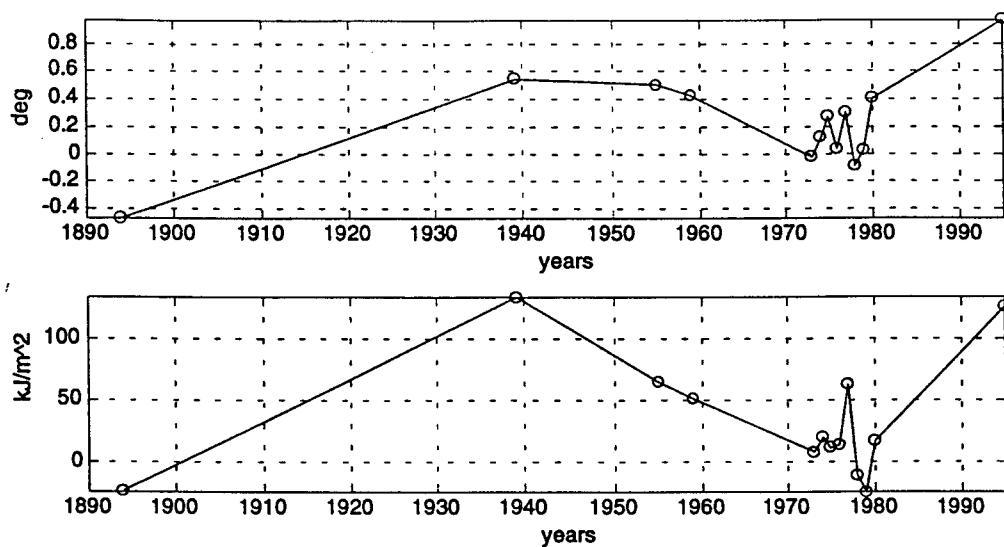
Fig. 7. The interannual anomalies of the maximum temperature (above) and heat content (x10^4) (below) of the Atlantic Water in region 2 - the region of Frans-Josef Land.
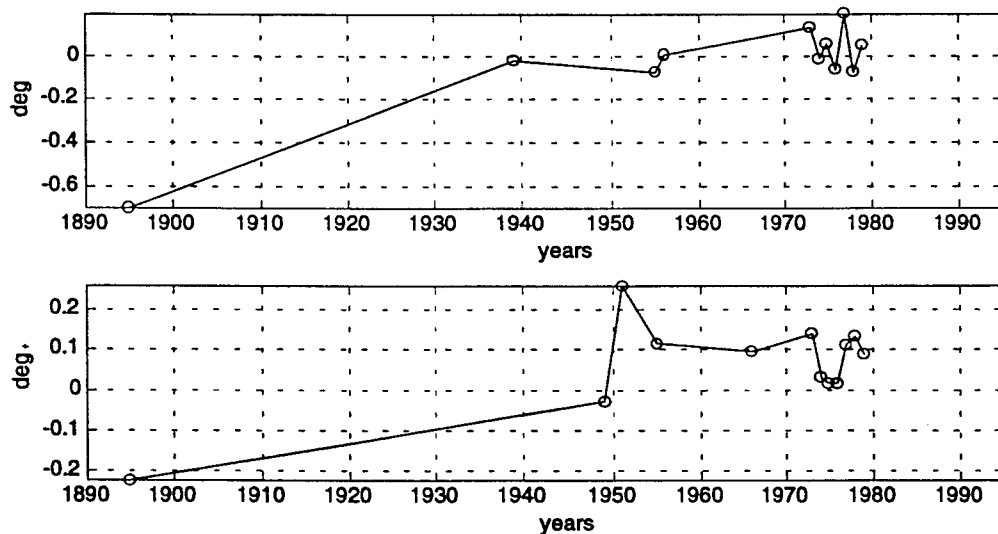
Fig. 8. The interannual anomalies of the maximum temperature of the Atlantic Water in region 3 - the region to the northwest of Severnaya Zemlya (above). The interannual anomalies of the average temperature of the Atlantic Water in region 4 - the region to the northeast of Severnaya Zemlya (below).

All of these characteristics of the Atlantic Water in this region covary. One displacement of the local maximum between 1939 and 1979 can be seen in Fig. 9.

Region 7 - the Chukchi Plateau. Coordinates: 160°W-180°W (sometimes, depending on bottom relief - 155°W-180°W), 74°N-79°N. There are 144 stations in the ODB, 65 of them chosen for the determination of interannual variability. The maximum temperature increased to 1995 by 0.3°, and the average temperature increased by 0.1° between 1950 and 1980 (Fig. 10). During the 1950-80 period, the changes in these characteristics were 5 times less.

Region 8 - the continental slope of the Chukchi Sea. This region is situated between the southern margin of the Arctic Basin and 74°N, and between 150°W and 180°W. There are 74 stations in the ODB, 36 of them chosen for the determination of interannual variability. The data in this region characterize the same years as in region 7. However, according to the observations of the American submarine, 1995 is rather colder than, or equal to, other years (Fig. 11).

Region 9 - the Beaufort Sea. This region is situated between the southern margin of the Arctic Basin and 74°N, and between 130°W and 150°W. There are 828 stations in the ODB, 46 of them chosen for the determination of interannual variability. The decrease in average temperature of the Atlantic Water from the 1950-60 period to 1968 by 0.07° can be noted in Fig. 12. Three to ten stations were used to calculate the characteristics of the Atlantic Water for each year in Fig. 12. Note that two stations in 1995, obtained in this region, are not shown in the Fig. 12. These stations have not passed through the algorithm of formal calculations and comparisons with the climatic characteristics. However, a comparison of these two stations with neighboring (up to 25 km) ones shows, that the temperature in 1995 is close to the temperature in 1969 and is lower than in 1951.

Region 10 - the eastern part of the Mendeleev-Alpha Ridge. This region is located between the Canada and the Makarov Basins within the limits of 138°W-180°W. There are 108 stations in the ODB, 101 of them chosen for the determination of interannual variability. According to Fig. 13, it is possible to say that 1995 was one of the coldest in the whole period of observations, since 1948.

Region 11 - the continental slope of the Canadian Arctic Archipelago. This region is located between the southern margin of the Arctic Basin and 83°N, and between 100°W-130°W. There are 28 stations in the ODB, 20 of them chosen for the definition of interannual variability. This region looks like a narrow belt between the shelf and more northern regions. Our data characterize only three years. It is possible to note, that 1965 was warmer than the period 1957-58 (Fig. 14).

Region 12 - the western part of the Mendeleev-Alpha Ridge. This region is located between the Canada and the Makarov Basins within the limits of 76°W-138°W. There are 53 stations in the ODB, 45 of them chosen for the definition of interannual variability. The average temperature in this region varies within the limits of 0.05°. An increase in average temperature from 1955 to the end of 60's and a distinct decrease from the 60's to 1974 is observed (Fig. 14, 15).

Region 13 - the eastern part of the Makarov Basin or the Basin of Podvodnikov. This region is located to the south of the region 15. The southern margin of the region 13 is: 150°E-160°E, 81° N; 160°E-165°E, 80°N; 165°E -180°E, 79°N. There are 69 stations in the ODB, 68 of them used for definition of interannual variability. The warmest year in this region was 1965. The coldest were 1941 and 1995 (Fig. 15, 16). Note that only one station was obtained here in 1941 during the expedition of the aircraft "USSR H-169".
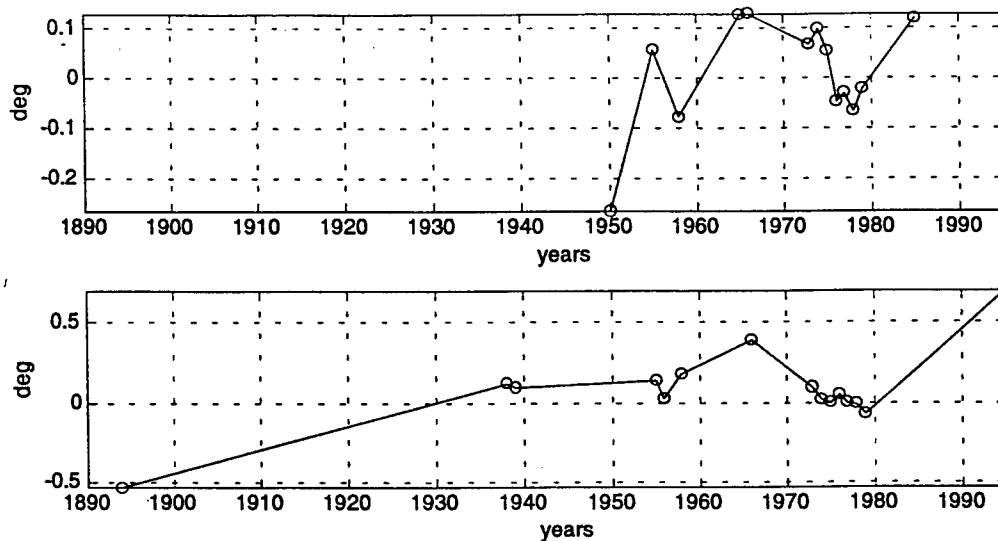
Fig. 9. The interannual anomalies of the average temperature of the Atlantic Water in region 5 - the eastern part of the Lomonosov Ridge (above). The interannual anomalies of the maximum temperature of the Atlantic Water in region 6 - the eastern part of the Amundsen Basin (below).
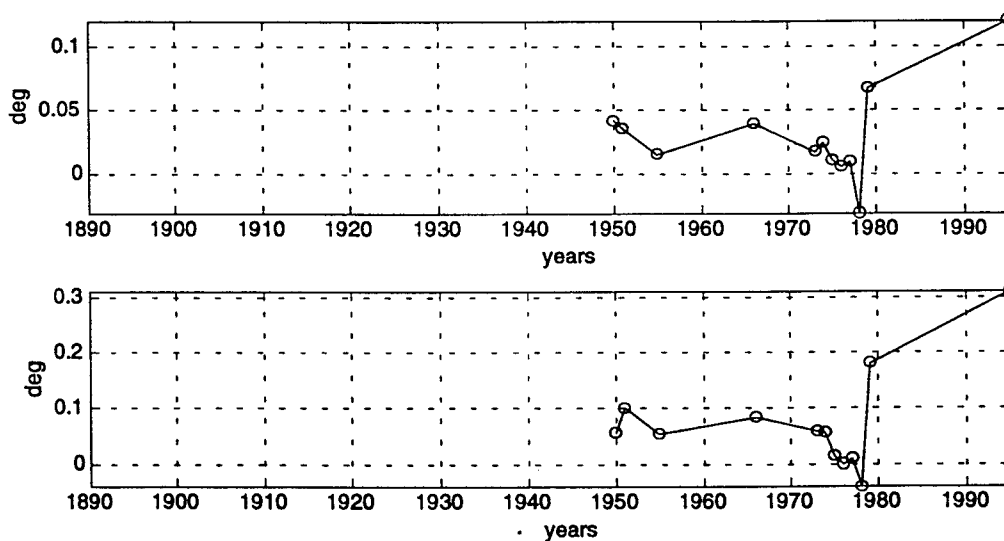
Fig. 10. The interannual anomalies of the average temperature (above) and the maximum temperature (below) of the Atlantic Water in region 7 - the Chukchi Plateau.

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Fig. 11. The interannual anomalies of the average temperature (above) and the maximum temperature (below) of the Atlantic Water in region 8 - the continental slope north of the Chukchi Sea.
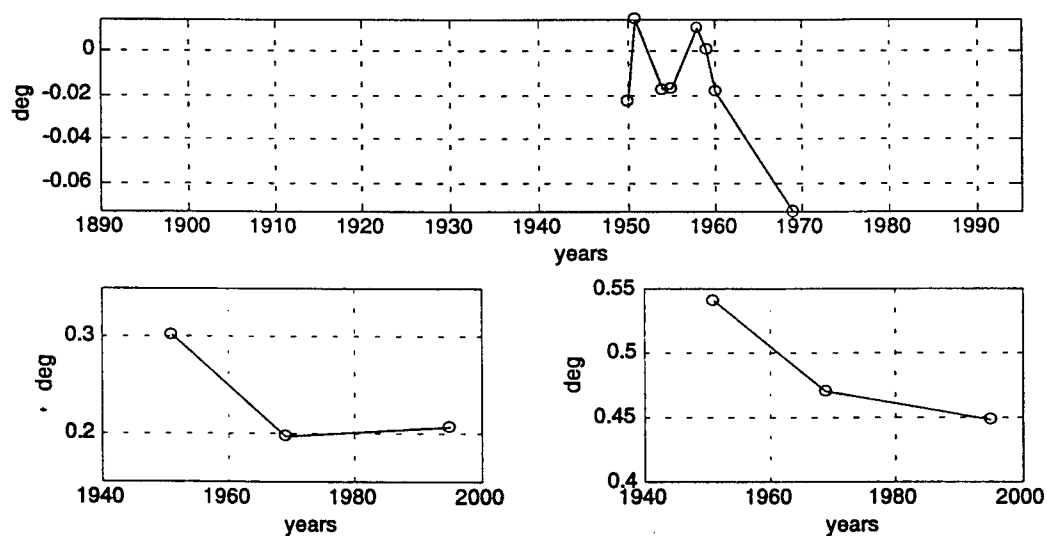
Fig. 12. The interannual anomalies of the average temperature of the Atlantic Water in region 9 - the Beaufort Sea (above). The temporal variations of the average (left) and maximum (right) temperature of the Atlantic Water in region 9 - the Beaufort Sea (below).

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Fig. 13. The interannual anomalies of the maximum (above) and the average (below) temperature of the Atlantic Water in region 10 - the eastern part of the Mendeleev-Alpha Ridge.
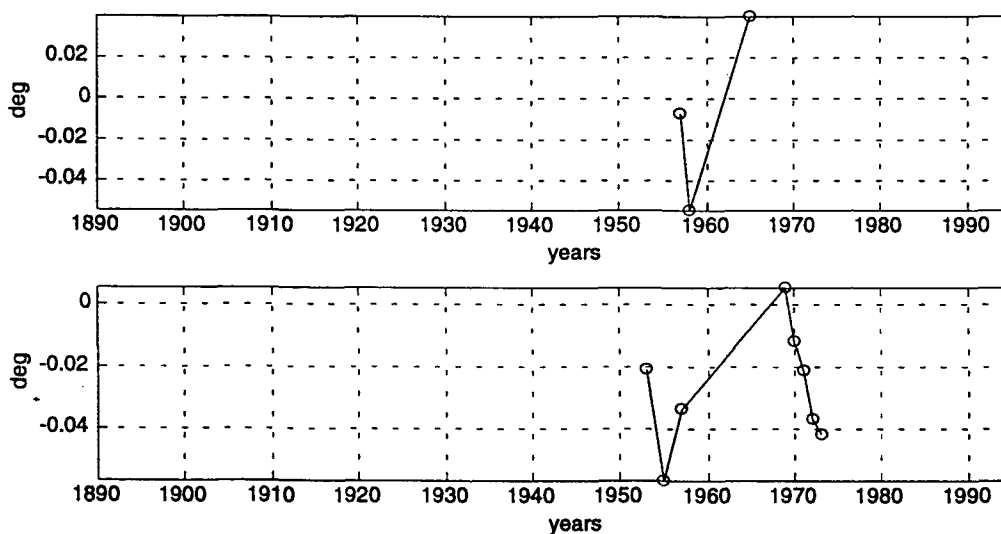
Fig. 14. The interannual anomalies of the average temperature of the Atlantic Water in region 11 - the continental slope of the Canadian Arctic Archipelago (above) and in region 12 - the western part of the Mendeleev-Alpha Ridge (below).

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Fig. 15. The interannual anomalies of the maximum temperature of the Atlantic Water in region 12 - the western part of the Mendeleev-Alpha Ridge (above) and in region 13 - the eastern part of the Makarov Basin (or Basin of Podvodnikov) (below).

Fig. 16. The interannual anomalies of the average temperature of the Atlantic Water in region 13 - the eastern part of the Makarov Basin (or Basin of Podvodnikov) (above) and in region 14 - the western part of the Lomonosov Ridge (below).

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Region 14 - the western part of the Lomonosov Ridge. This region is located between the Makarov and Amundsen Basins within the limits of 40°W-75°W, 85°-90°N. There are 33 stations in the ODB and all of them are used for the definition of interannual variability. Warming from 1955 to 1958, then cooling up to 1975 and warming up to the 1980's can be seen (Fig. 16).

Region 15 - the western part of the Makarov Basin or the Makarov Basin itself. The coordinates of the region are: 40°W-90°W, 88°N; 90°W-157°W, 89°N; 90°W-145°W, 87°N; 145°W-160°W, 86.3°N; 160°W-180°W, 85.5°N; 162°E-180°E, 83.5°N; 157°E-162°E, 85°N. There are 34 stations in the ODB, 33 of them chosen for the definition of interannual variability. The year 1955 was the warmest and 1995 was the coldest in this region (Fig. 17).

Region 16 - the Lincoln Sea. This region is located between the southern border of the Arctic Basin and 85°N, and between 40°W-75°W. Because of the shallow depths, the majority of stations do not contain Deep Water of the Arctic Basin. Therefore the Atlantic Water sits on the ocean bottom. So, not one station has passed the algorithm of formal calculations. Nevertheless, it would be interesting to compare the results of the ice camp "Narwal" 1994 with other data. The POLEX profiles of 1955 and 1973-79 have appeared to be the nearest to the stations of 1994. The distance is equal to 100 km, so the direct comparison is not ideal in this case. Therefore, an approximate comparison with climatic characteristics was made. It appears that the Atlantic Water in 1994 was cooler by approximately 0.1° and 0.15°, compared with 1955 and the period 1973-79.

Region 17 - the southern part of the Canada Basin. The margins of the whole Canada Basin are chosen as following: 150°W- 165° W, 79°N-82°N; 150°W-155°W, 73°N-78°N; 130°W-150°W, 75°N-82°N; 115°W-130°W, 82°N-84°N. Region 17 goes up to 79°N. There are 334 stations in the ODB, 122 of them chosen for the definition of the interannual variability. The range of variability of the average and the maximum temperature of the Atlantic Water in this region is less than 0.9°. The average temperature in 1995 is near the climatic value and somewhat warmer than in 1973 (Fig. 18). The heat content in 1995 is medium also, but less than in 1973. The opposite tendencies are due to the decrease in Atlantic Water thickness from 1973 to 1995.

Region 18 - the northern part of the Canada Basin. This region is located within the limits of Canada Basin margins and to the north of 79°N. There are 70 stations in the ODB, 63 of them chosen for the determination of interannual variability. The ranges of the interannual variability of the maximum and average temperatures are 0.1° and 0.05°. According to the average temperature value, 1995 is cooler compared with climatic characteristics, but the heat content is near average in 1995.

Region 19 - the western part of the Amundsen Basin. The region is situated within the bounds of the Amundsen Basin (see region 6) and to the west of 90°E. There are 128 stations in the ODB, 53 of them used for the determination of interannual variability. Region 19 is characterized by an increase in average temperature by approximately 0.15° from 1937 to 1957, and a subsequent decrease to 1979 by 0.1° (Fig. 19).

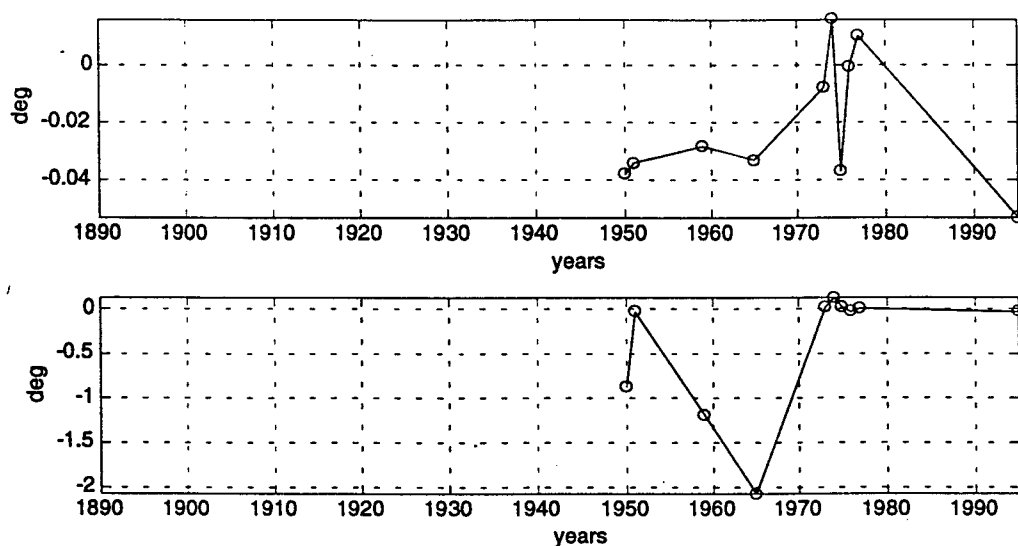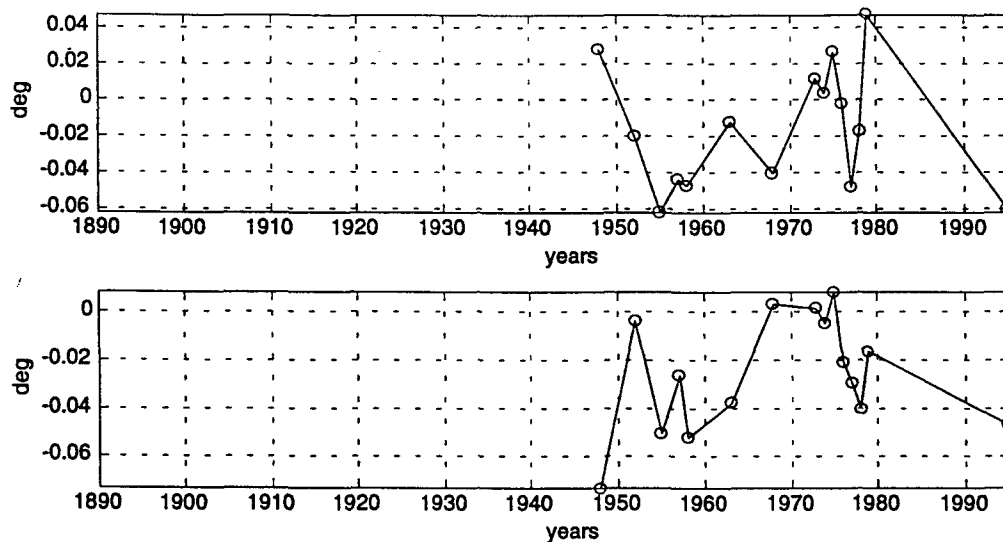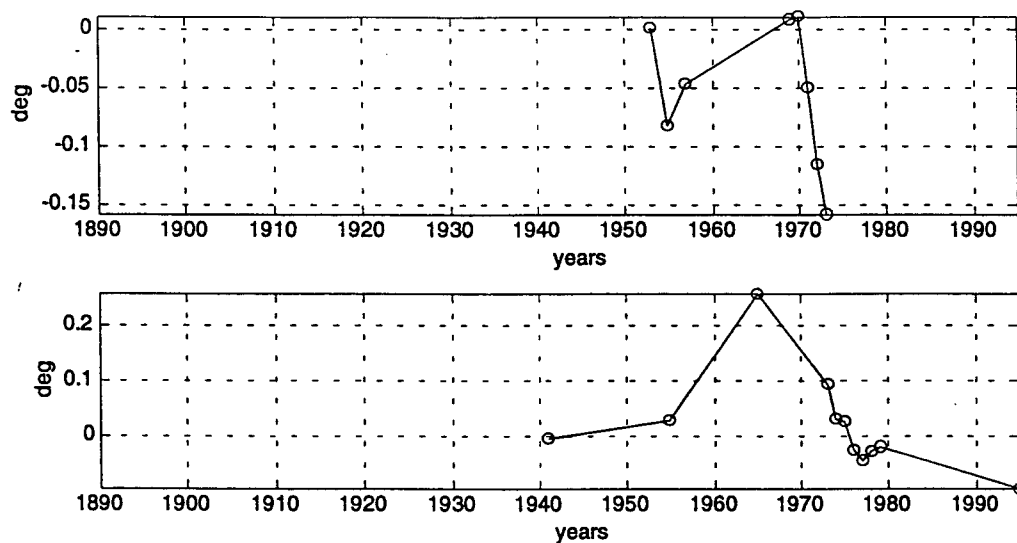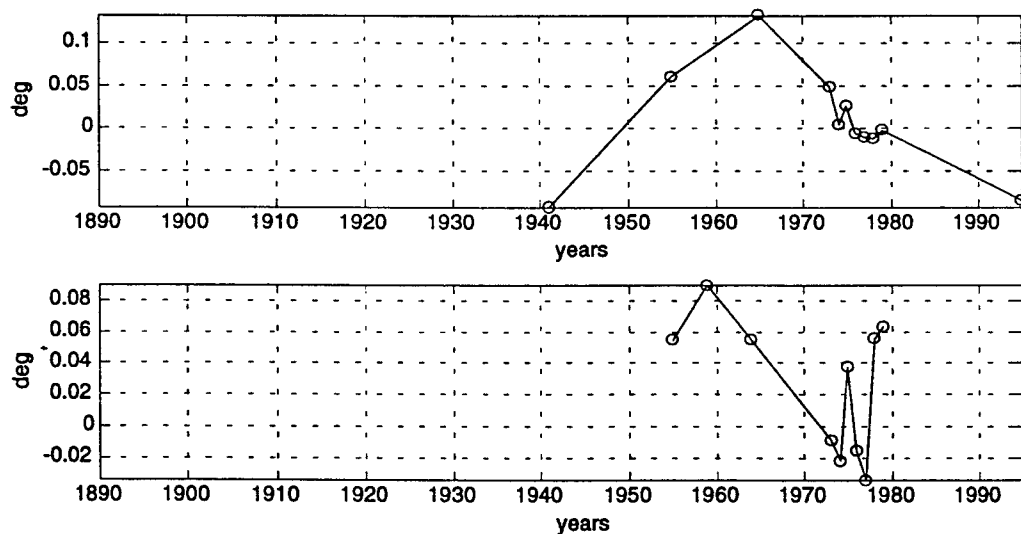**Fig. 17.** The interannual anomalies of the average (above) and the maximum (below) temperature of the Atlantic Water in region 15 - the western part of the Makarov Basin (or Makarov basin itself).

Fig. 18. The interannual anomalies of the average temperature of the Atlantic Water in region 17 - the southern part of the Canada Basin (above) and in region 18 - the northern part of the Canada Basin (below).

Fig. 19. The interannual anomalies of the average temperature of the Atlantic Water in region 19 - the western part of the Amundsen Basin (above) and in region 20 - the Morris Jesup Plateau (below).
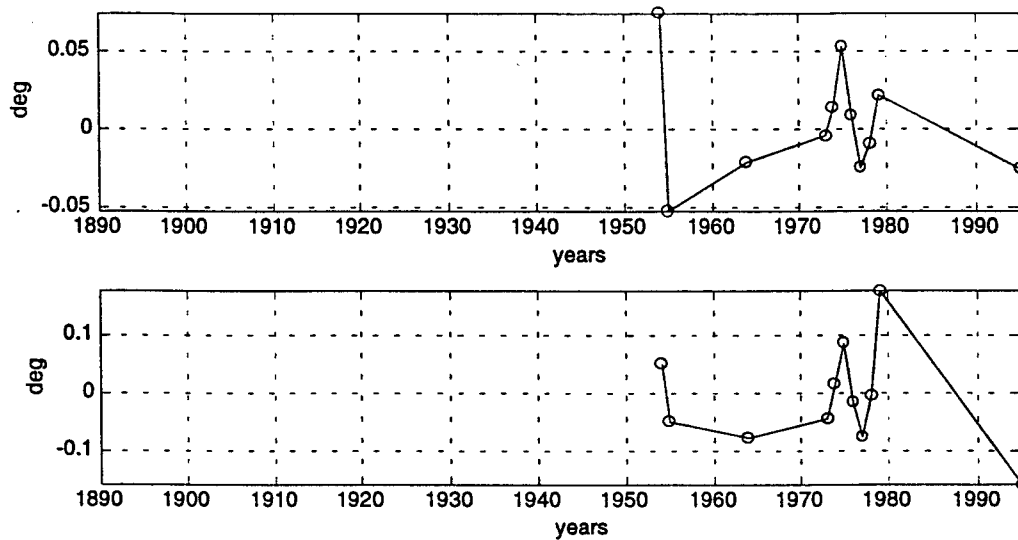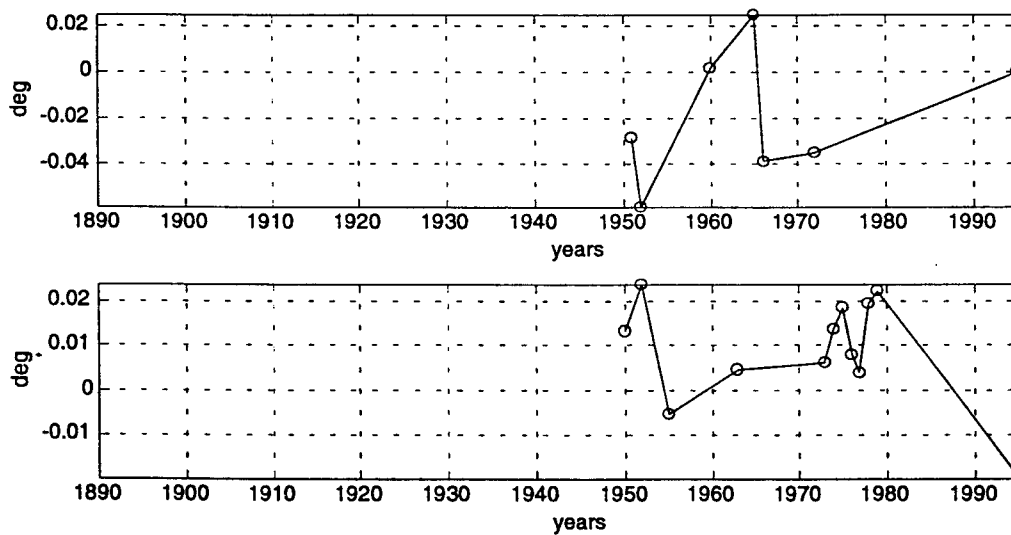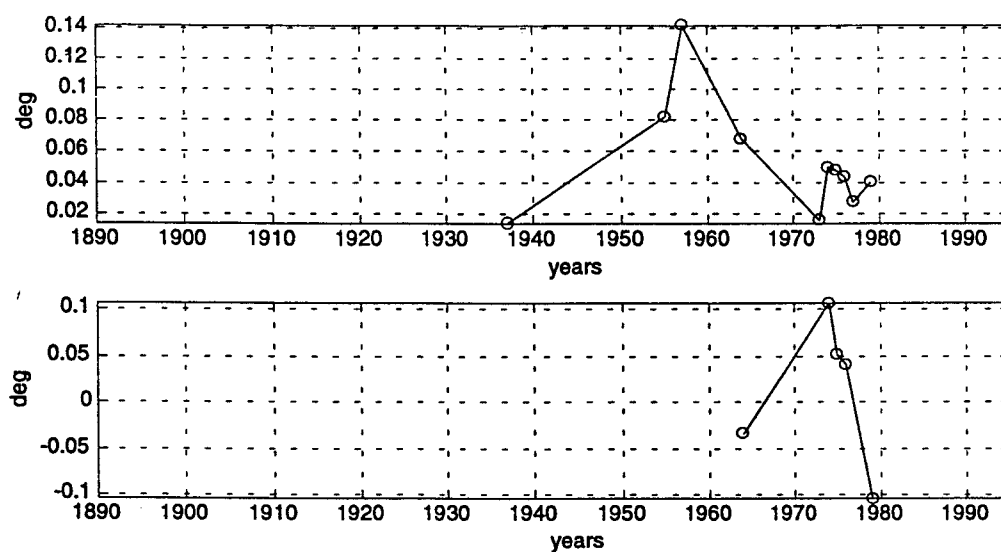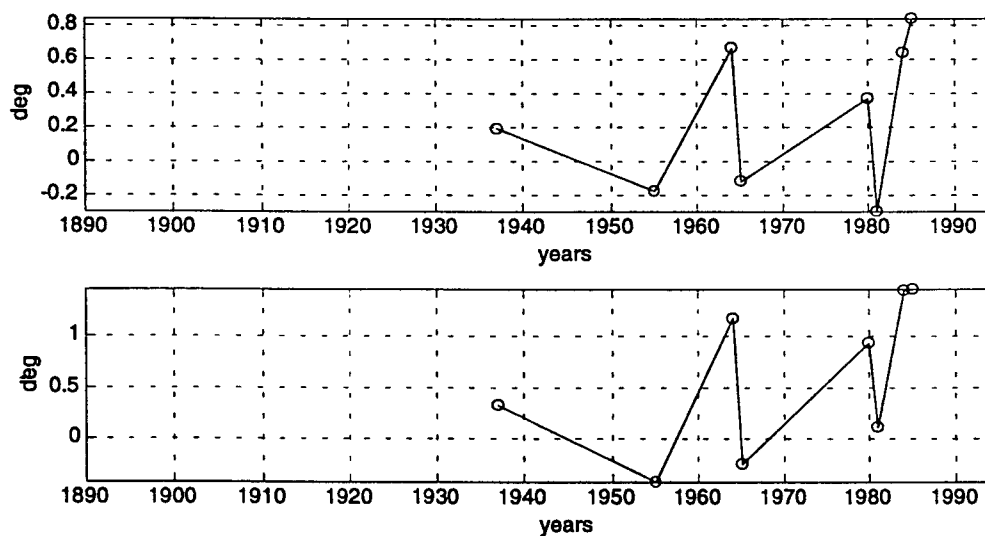

Fig. 20. The interannual anomalies of the average (above) and the maximum (below) temperature of the Atlantic Water in region 21 - the region of Atlantic Water inflow through the Fram Strait.

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Region 20 - the Morris Jesup Plateau. This region borders the Amundsen Basin on the north, and is located above 83.5°N and between 0°-40°W. There are 62 stations in the ODB and all of them are used for the determination of interannual variability. The region corresponds to separate parts of the large-scale bottom relief and structure VII of the water masses (Fig. 1). The temporal record of the average temperature, the maximum temperature and the heat content are very similar in this region. The whole range of variability of the average temperature is 0.1° (Fig. 19). An increase in values of all characteristics is seen from 1964 to 1974, followed by a decrease from 1974 to 1979.

Region 21 - the region of the Atlantic Water inflow through the Fram Strait. This region is located between the southern margin of the Arctic Basin and 83.5°N, and between 0°-40°W. There are 70 stations in the ODB, 24 of them chosen for the determination of interannual variability. The range of the variability of the maximum and the average temperature in this region exceeds those in the region of the Morris Jesup Plateau. This is due to the influence of the Atlantic Water recirculation and the frequent shift of the Fram Strait frontal zone to the west in the eastern part of the region 21.

To reduce the influence of the Atlantic Water inflow on the variability, let us consider a region from the Greenland shelf up to 5°W, and to the south of 83.5°N. In this new region there are less stations than in all of region 21. However, some stations have average temperatures of more than 0.9° and maximum temperatures in the range 1.5-2°. Such temperatures are more common for the zone of the Atlantic Water recirculation, than for the zone of the outflow. When the east margin of the region is shifted up to 10°W, only 4 stations, obtained in a single year, remained under consideration. Therefore, it is impossible to determine interannual variability in this region on the basis of our data only.

VI. DISCUSSION

Variations in the average temperature, the maximum temperature, the thickness and the heat content of the Atlantic Water shown in Figures 5-19, are not always correlated with each other. The discrepancy in variations of the maximum temperature, and other characteristics of the Atlantic Water, is partly the result of the technique of the measurements. Most of the data analyzed have been obtained from bottle measurements at standard depths. None of these depths necessarily coincide with the depth of the actual temperature maximum. Hence, the measured value may be less than the absolute maximum in the temperature profile. Moreover, when comparing different experimental profiles with each other, or with the climate profiles, in 35% of the cases variations of the mean temperature and the heat content correlate inversely. Therefore, for computation of changes in the heat content, it is necessary to take into account both the average temperature and the thickness of the Atlantic Water layer.

Significant influence of the thickness of the Atlantic Water layer on the heat content was pointed out in [10] after the analysis of about 700 POLEX stations of 1955, 73-76. According to the present analysis and the results of [10], we have established that changes in the thickness of the Atlantic Water layer are due, mainly, to the vertical migration of the lower boundary of this layer. Vertical displacements of the lower boundary may be 10 times greater than those of the upper boundary.

Changes in the thickness of the Atlantic Water layer cause variations in the water temperature and the sound speed, averaged over the water column. Therefore, changes in the heat content of Atlantic Water can be monitored by using the methods of acoustic thermometry.

The range of interannual variations in the Atlantic Water heat content differs in different regions of the Arctic Basin. We compared mostly the data of 1955-85, because only this time period is represented in our data base for most of the regions in the Arctic Basin. We did not consider those extreme values which had been evaluated from only one or two stations (see, for example, region 14, 1959).

The greatest anomalies are marked in regions 1 and 21. As mentioned above, this is due, mainly, to the impossibility of separating the temporal and spatial variations in these regions. In the northeastern part of

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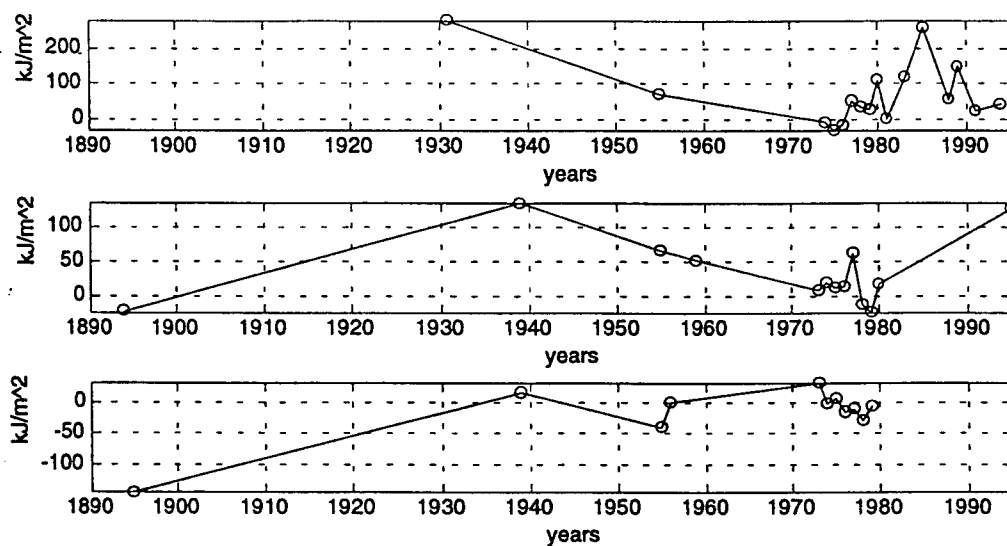
Fig. 21. The interannual anomalies of the heat content (x10⁴) of the Atlantic Water in the north-eastern part of region 1 - the region of Svalbard Island (above), in region 2 - the region of Frans-Josef Land (middle), and in region 3 - the region to the northwest of Severnaya Zemlya (below).

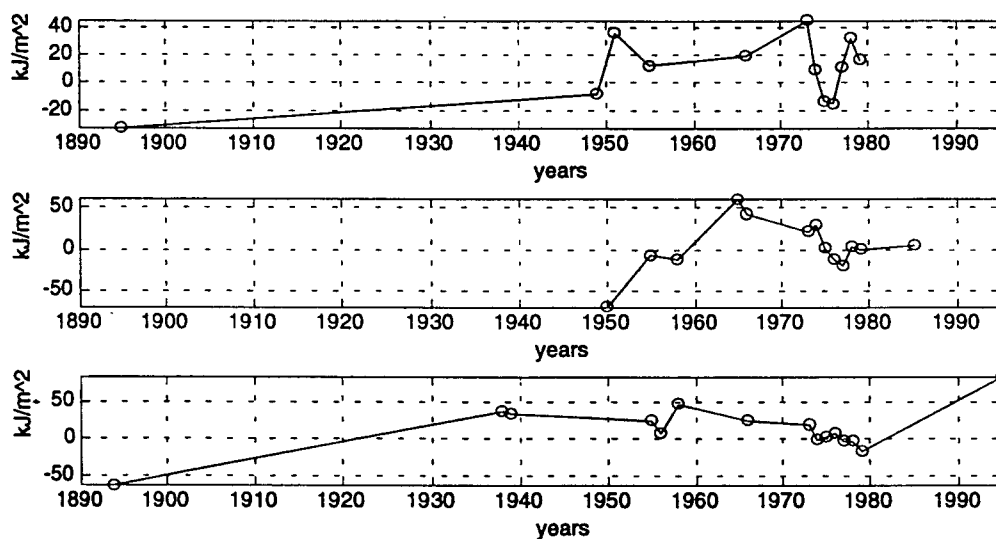**Fig. 22.** The interannual anomalies of the heat content (x10⁴) of the Atlantic Water in region 4 - the region to the northeast of Severnaya Zemlya (above), in region 5 - the eastern part of the Lomonosov Ridge (middle), and in region 6 - the eastern part of the Amundsen Basin (below).

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region 1, where we assume that the spatial variations are completely separated, the variability range is about 20×10^5 kJ/m^2 (Fig. 21), while in regions 2 and 3 this value is 2-3 times less than that in region 1 (Fig. 21). In regions 4-6 the extreme anomalies are even less - 5-6×10^4 kJ/m^2 (Fig. 22). Such values do not exceed 3-4×10^4 kJ/m^2 in regions 12-14 (Fig. 24, 25), and 1.5-2.5×10^4 kJ/m^2 - in regions 10, 15, and 17-19 (Fig. 24, 25). Such spatial change in the anomalies of the heat content is, in general, in good agreement with the hypothesis predicting a decrease in both the mean value and the variation range of the heat content, while the Atlantic Water spreads into the Arctic Basin according to the circulation scheme (Fig. 3).

It is necessary to note, that the smallest range of the variability has been observed in the regions of the Chukchi Plateau (regions 7, 8) and the Beaufort Sea (region 9) (Fig. 23) which are not the most peripheral regions of the circulation scheme. At present, we have not yet found any reasonable explanation for this fact.

Observing interannual variations of the Atlantic Water heat content in various regions, one can see that long-term changes exceed short term variations (Fig. 21-26). A similar observation was made in [10] after the analysis of the interannual variability of Atlantic Water in 1950, 1955, and 1973-76 [10]. This is generally atypical of temporal variations in oceanic water masses - the amplitude of fluctuations commonly decreases with an increase in the time of averaging.

The results presented in this report confirm some of the conclusions drawn in earlier studies. Considerable warming from the beginning of this century until the 1930-40's, is described in detail in several Russian publications (for example [34]). In addition to the warming of the Atlantic Water clearly observed in regions 2-4, and 6 (Fig. 21, 22), there was also mention, in the literature, of many other observations of warming in the Arctic in 1930-40's. The reduction of areas of the glaciers on Svalbard, Greenland and Frans-Josef Land relative to the 1890-1900s was observed in 1930-40. Vasilevsky Island in the Laptev Sea, explored in detail in 1912, was covered with fossil ice, sand and clay. However, this island had been transformed into an underwater bank in as little as 24 years, by 1936. The areas of other similar islands were reduced sixfold between 1910 and 1940. Furthermore, warming of the average air temperature measured at Arctic meteorological stations, the migration of southern varieties of fishes to the North, the increase in the temperature in the North Cape current, and the reduction of the ice cover in the Siberian seas during 1905-1940 were also referred to in numerous publications. It is known, that the motor sailing ship *Knipovich* passed north of Frans Josef Land in 1932. There was also no ice over the "Northeast Passage" in the Siberian seas in 1935, while in 1901 the powerful icebreaker *Ermak* could not overcome the ice north of Novaya Zemlya. In 1912 the ship *St. Foka* failed while trying to reach Frans Josef Land from the south side, and the ship *St.Anna* was blocked by ice near the Yamal coast.

The latest data on the Atlantic Water characteristics indicate warming similar to that observed at the beginning of the century. Among the data available for the present study, confirmation of the current warming in the Arctic Ocean follows from the results of the transarctic cruise of an American submarine in the SCICEX'95 experiment in 1995 (Fig. 21-26). Evidence of the present warming of the Atlantic Water is also shown in recent works [11, 12, 17, 23, 24]. Observations pointing at other aspects of the current warming in the Arctic, such as retreat of the glaciers, have not yet been published.

The spatial distribution of the temperature anomalies along the SCICEX'95 track, show that the warmed Atlantic Water is spreading over the Eurasia Basin and further to the Chukchi Plateau (regions 2, 3, 6, 7, 8; Fig. 21-23). The regions of the Canadian and Makarov Basins, and the Mendeleev-Alpha Ridge, are cooling slightly at present (regions 10, 13, 15, 17, 18; Fig. 24, 25, 26). One of the main reasons for the present positive anomalies in the Atlantic Water temperature is assumed to be the penetration of relatively warm water through Fram Strait in 1985 (northeastern part of the region 1; Fig. 21).
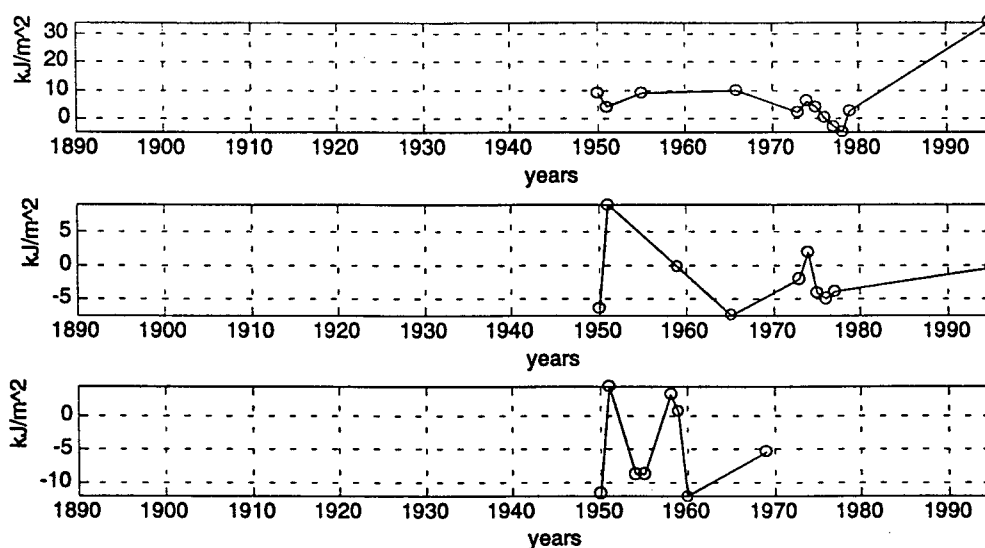
Fig. 23. The interannual anomalies of the heat content (x10^4) of the Atlantic Water in region 7 - the Chukchi Plateau (above), in region 8 - the continental slope north of the Chukchi Sea (middle), and in region 9 - the Beaufort Sea (below).
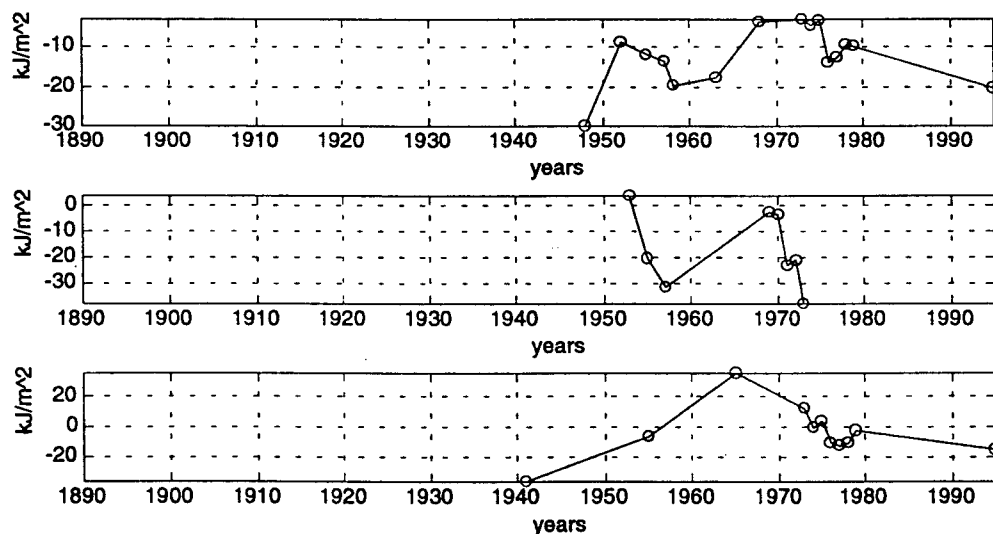
Fig. 24. The interannual anomalies of the heat content (x10^4) of the Atlantic Water in region 10 - the eastern part of the Mendeleev-Alpha Ridge (above), in region 12 - the western part of the Mendeleev-Alpha Ridge (middle), and in region 13 - the eastern part of the Makarov Basin (or Basin of Podvodnikov) (below).

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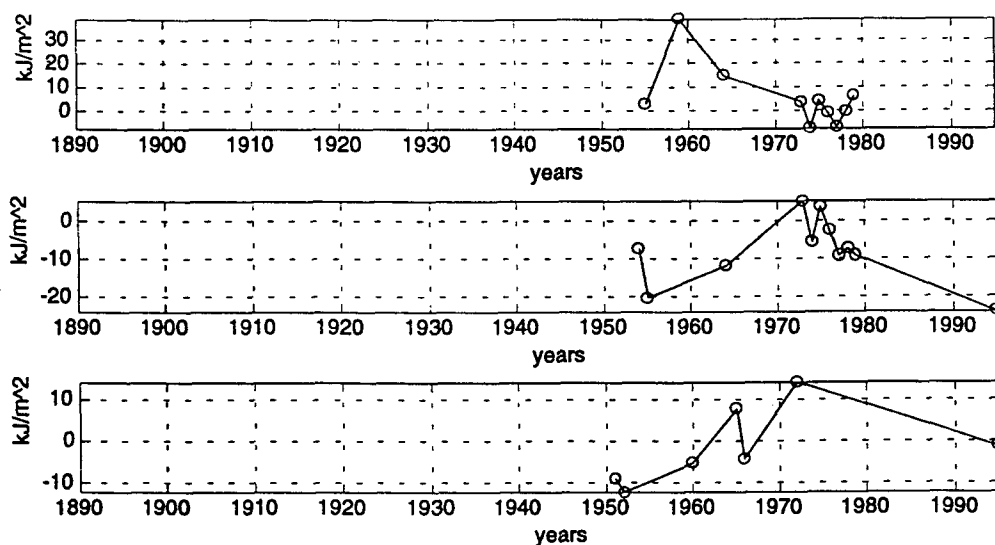
Fig. 25. The interannual anomalies of the heat content (x10⁴) of the Atlantic Water in region 14 - the western part of the Lomonosov Ridge (above), in region 15 - the western part of the Makarov Basin (or Makarov Basin itself) (middle), and in region 17 - the southern part of the Canada Basin (below).
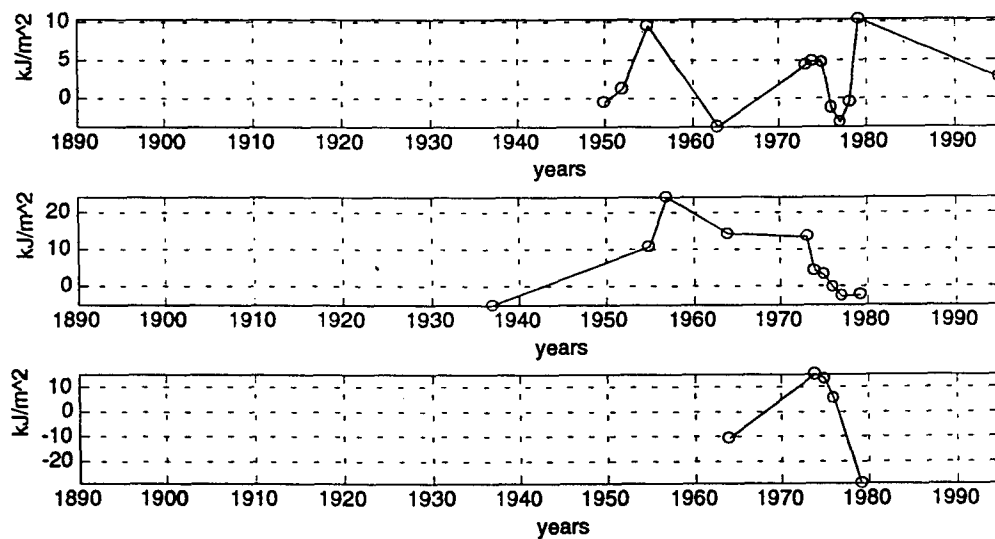

Fig. 26. The interannual anomalies of the heat content (x10⁴) of the Atlantic Water in region 18 - the northern part of the Canada Basin (above), in region 19 - the western part of the Amundsen Basin (middle), and in region 20 - the Morris Jesup Plateau (below).

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The data of 1995, as well as those of some other years, illustrate that not only the magnitude, but also the sign of variations in the Atlantic Water characteristics do not always coincide in different regions even though they may be adjacent to each other (Fig. 5-26). A similar conclusion was also reached after an analysis of the Atlantic Water characteristics in 1955 and in 1973-76 in three sub-basins of the Arctic Basin - the European (regions 1-6), the Canadian (regions 7-18), and the zone of the Atlantic Water outflow (regions 19-21) [10]. It is unlikely that the spatial change in the anomaly sign can be attributed to only the phase delay along the circulation stream of the Atlantic Water. Apparently, both the variability of the Atlantic Water inflow through the Fram Strait, and the diffusion and transformation of the Atlantic Water within the Arctic Basin can cause the interannual variability.

VII. CONCLUSIONS

Following the modern views on the water structures and the circulation scheme in the Arctic Basin, we have distinguished the ocean regions by relative homogeneity of the interannual variability, observed in the experimental data.

We have compared all CTD profiles collected in our data base, with the climatic fields in each of these regions, and determined the ranges of interannual variability of the Atlantic Water characteristics for those regions.

It is established, that long-term changes in the Atlantic Water characteristics have amplitudes greater than those of the short term. The results obtained in the present study are very important for realistic modeling of long-term acoustic thermometry on trans-Arctic tracks.

The analysis of the results presented, allows us to conclude that the latest warming of the water in the Arctic Ocean is spread over the Eurasian Basin and further to the East, up to the Chukchi Plateau. This warming is apparently due to the inflow of abnormally warm waters into the Arctic Basin through the Fram Strait in 1985. As a counterbalance to this, extensive regions of the Canadian Basin are, at present, colder relative to the climatology. Analogous warming of the Atlantic Water was observed in the European part of the Arctic Basin in 1930-40s.

We have also concluded, that changes in the Atlantic Water, flowing into the Arctic Basin, are not the only source causing the interannual variability of the Atlantic Water far from the European continental slope and the Nansen Basin. The diffusion and the transformation of the Atlantic Water inside the Arctic Basin play important roles in the generation of interannual fluctuations.

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